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SOUND REDUCTION INDEX OF DRY-WALL MATERIALS: EXPERIMENTAL COMPARISON OF MODEL PREDICTIONS AND TRANSMISSION ROOM MEASUREMENTS

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In the construction industry, it is often necessary to check the dynamic properties of the products and to relate them to their acoustic quality. A typical example is the production of building materials for the construction of dry walls. In this context, the availability of a quick, though reliable, method to be applied in-situ or to small portions of material can be of great help, both for quality control and for research and development purposes. Some relatively simple methods have been recently proposed, that start from the determination of the bending stiffness and the losses to estimate the acoustic insulation properties of the material, that is, the sound reduction index at different frequencies. In particular, the bending stiffness can be found either from the natural frequencies of beams cut from the product, or from the space average of the point mobility function measured on the whole leaf. Plasterboard is very popular because it is lightweight, modular and easy to install, its technical characteristics depending on thickness, type of facings and gypsum chemical composition. An interesting variant is offered by gypsum fibreboard, featuring considerably improved mechanical and water resistance properties. Plasterboard and gypsum fibreboard production is therefore an excellent test bench to assess the capabilities of the simple methods outlined in the literature. In this paper, the sound reduction indices obtained from both natural frequency and point mobility methods have been compared to measurements performed in double sound transmission room according to ISO 10140 series standards, to the aim of pointing out the potential and the limits of the two methods and setting the path for future developments. Tested materials include plasterboard and gypsum fibreboard.

Keywords: plasterboard, fibreboard, sound reduction index

1. Introduction

Early application of gypsum-based panels as construction materials dates back to the first half of the twentieth century in the US, and has been finding a continuous development since then due to their unique characteristics, like low cost, good workability, easy transport and quick laying. The issuance of strict regulations regarding thermal and acoustic quality has further increased the preference for these materials in different sectors [1,2,3], such as building construction and transport, as they are particularly suitable to the tailored optimisation that new technologies provide nowadays.

One of the most essential features that a material used for partitions in the construction industry must possess is an excellent sound reduction index. However, once the material has been designed, validated and put into production, the control of acoustic properties becomes sporadic. As a consequence, any intentional or accidental variation in the production process may compromise the sound insulation characteristics of the material without notice.

For this reason, the availability of rapid and reliable methods to quality-check the sound reduction performances of the product may be of great importance.

In the present paper, double transmission room measurements on plasterboard and gypsum fibreboard are compared to the sound reduction indices obtained by two experimental methods that have been developed and applied to sandwich structures [4]: natural frequency and point mobility methods, the former being more suitable to production testing and the latter to in-situ control activities.

Particular attention is dedicated to the estimation of internal, radiation and adjoining-structure losses.

2. Materials and methods

2.1 Analytical models

The sound reduction index R in decibels for a partition is given by

$$R = -10 \log \tau_d \ , \tag{1}$$

where τ_d is the sound transmission coefficient for diffuse incidence, defined as

$$\tau_d = 2 \int_0^{\varphi_{lim}} \tau(\varphi) \cos\varphi \sin\varphi \, d\varphi \ , \tag{2}$$

φ_{lim} being the limit angle for the maximum sound incidence of the acoustic wave on the panel. The sound transmission coefficient $\tau(\varphi)$ for a thin homogeneous plate as a function of the critical frequency, f_c, can be written as [5]:

$$\tau(\varphi) = \left\{ \left[1 + \frac{\mu''\omega}{2\rho c} \cos\varphi \left(\frac{f}{f_c}\right)^2 (\sin\varphi)^4 \eta_{tot} \right]^2 + \left[\frac{\mu''\omega}{2\rho c} \cos\varphi \left(\frac{f}{f_c}\right)^2 (\sin\varphi)^4 - 1 \right]^2 \right\}^{-1} , \tag{3}$$

where μ'' is the mass per unit area, ω the angular frequency, ρc the wave impedance of the air at room temperature and η_{tot} the overall loss factor. For homogeneous single leaf panels, the critical frequency is defined as the frequency at which the trace matching between flexural waves on the plate and waves in the surrounding medium can occur:

$$f_c = \left(\frac{c^2}{2\pi}\right) \sqrt{\frac{\mu''}{D}} \ , \tag{4}$$

with D bending stiffness of the structure. For homogeneous structures, D can be considered constant in the frequency range of interest. More generally, for composite materials, the bending stiffness is frequency dependent and then D can be replaced by a frequency dependent apparent bending stiffness D_x.

2.1.1 Bending stiffness from natural frequency measurements

The experimental determination of the apparent bending stiffness can be easily carried out on a beam. For a beam, each natural frequency f_n can be related to the bending stiffness of the specimen at that frequency, D_{xn}. In particular, the apparent bending stiffness D_{xn} of a beam, length L, can be obtained for the n-th mode with eigenfrequency f_n as:

$$D_{xn} = \frac{4\pi f_n^2 \mu' L^4}{\alpha_n^4} \ , \tag{5}$$

where μ' is the mass per unit length of the beam. The modal coefficients α_n depend on the boundary conditions and are reported in Table 1 for a beam with free ends.

Once a set of points (f_n, D_{xn}) is determined, the least square method can be applied to find the best fitting of a function describing the apparent bending stiffness trend for the specific structure type (sandwich, homogeneous, etc.).

Table 1: Modal coefficient values for the different *n* modes (free-free boundary condition).

n	1	2	3	4	≥ 5
α_n	4.73	7.85	11	14.14	$n\pi + \pi/2$

The method provides accurate predictions especially with symmetric sandwich structures [6].

2.1.2 Bending stiffness from point mobility measurements

When beams cannot be cut from the plates, it can be convenient to derive the apparent bending stiffness from point mobility measurements.

For a finite structure a space- and frequency-average of the real part of the point mobility is, in the mid and high frequency region, identical to the real part of the point mobility of an infinite structure made of the same material and having the same thickness [6]:

$$\mathrm{Re}\langle \bar{Y}(\omega)\rangle = \mathrm{Re}\big(Y_\infty(\omega)\big)\,. \tag{6}$$

This statement is valid if the modal density within a certain frequency band does not depend on boundary conditions, which is typical for the medium-high frequency range. In order to extend this assertion to the low frequency range, at least 5 modes have to be included within each frequency band to have a fair accuracy. As concerns the space-average of the mobility, for obtaining an approximation which is representative of the dynamic properties of the panel, the mobility has to be measured over a number of points large enough, and the points have to be randomly distributed over the panel surface. In this case, the frequency average of the mobility can be written as

$$\mathrm{Re}\langle \bar{Y}\rangle = \frac{1}{8\sqrt{D'\mu''}}\,, \tag{7}$$

where D' and μ'' are, respectively, the bending stiffness per unit width and the mass per unit area of the panel. The bending stiffness per unit width of the panel at the central frequency of each frequency band is therefore obtained as

$$D' = \frac{1}{64\,\mu''[\mathrm{Re}\langle \bar{Y}\rangle]^2}\,. \tag{8}$$

This solution proved to be a valid alternative to the method outlined in Section 2.1.1 in case of very large [7] or already-mounted panels, even when characterised by strongly asymmetric structure [8].

2.2 Experimental measurement campaigns

The goal of the experimental work is to compare the sound reduction indices predicted through natural frequency and point mobility techniques with the results of measurements performed in sound transmission room according to ISO 10140 series standards.

2.2.1 Sound transmission room measurements

The sound reduction index for the different panels has been determined according to ISO 10140 parts 1, 2, 4 on 1700 mm × 1090 mm specimens. In order to avoid sound leakage through the sides of the specimens fitted into the wall dividing the two hard rooms, a sealant (Perennator TX 2001 S) has been used to close the air gap between the wood frame and the plate. The sound pressure levels in the emitting and receiving rooms have been measured by using a L&D 824 sound analyser and subsequently space-averaged. The reverberation time has been measured using the interruption of a stationary pink noise. A sketch of the measurement set-up for the frame is given in Fig. 1.

(a) (b)

Figure 1: Installation of the plasterboard (a) and the gypsum fibreboard (b) panels in double transmission room according to ISO 10140-1, annex D.

2.2.2 Measurements on beams

To derive the natural frequencies of beam test samples, the beams have been suspended through elastic strings (Fig. 2). An accelerometer PCB type 352C33 has been placed at one side of the beam, while the specimen has been hit using an impedance hammer PCB type 086C03 at the other side. Once the natural frequencies are derived, the bending stiffness at a particular frequency can be computed using Eq. (5). The transducers have been connected to an OROS OR36 analyser. The software managing the analyser can compute the transfer function in real time.

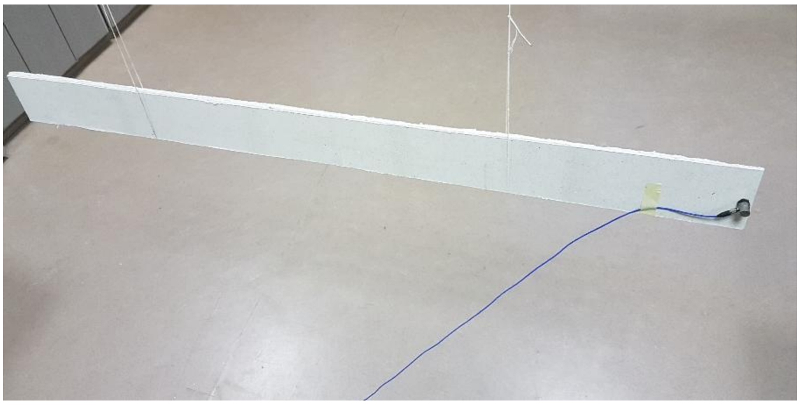


Figure 2: Beam measurement set-up.

The tests have been carried out on two samples with the characteristics given in Table 2.

Table 2: Size and weight for unit area of the test samples.

Sample type	Length [mm]	Height [mm]	Thickness [mm]	Mass/unit area [kg/m^2]
Plasterboard	1200	100	12.5	8.3
Gypsum fibreboard	1200	100	12.5	15.0

The impulse response was recorded with the analyser and post-processed using Audacity software and Aurora plugin in order to compute the structural reverberation time and derive the internal losses.

The same test samples have been used for the determination of the internal losses and the losses generated by the interaction with the adjacent structures, as described in [9]. In this case, the beams have been fitted to two heavy weight bricks by using Perennator putty (Fig. 3). Then, six reverberation time measurements have been carried out to obtain an average value.

Figure 3: Installation of the beam, fitted to two heavy-weight bricks by using Perennator putty.

2.2.3 Measurements on plates

For the application of the method based on point mobility measurements, two sample plates made of plasterboard and gypsum fibreboard have been suspended to elastic strings. The plates have dimensions 1200 mm × 1000 mm. Twenty measurement positions have identified on half of the plates assuming a vertical symmetry of the samples.

The transducers and the equipment are the same used for the measurements on the beams.

After the measurements, the space- and frequency-average of the point mobility function has been used to compute the apparent bending stiffness of the samples according to Eq. (8). The quality of the measurements and the inclusion of at least five modes within each extended band is crucial to provide a good estimation of the bending stiffness in the low frequency range [7].

2.2.4 Losses

In order to predict the sound reduction index through Eq. (3), a proper estimation of the total losses η_{tot} of the samples tested in sound transmission room is necessary.

The total loss factor is given by the sum of three contributions: the internal losses η_{int}, the losses caused by the interaction with the adjoining structures η_{adj}, and the radiation losses η_{rad}:

$$\eta_{tot} = \eta_{int} + \eta_{adj} + \eta_{rad} \tag{9}$$

The sum of the internal losses and the losses due to the adjoining structures can be estimated by measuring the reverberation time on beams mounted in a similar condition as the panels in sound transmission room, that is to say, by means of a wooden frame sealed with putty (Fig. 4), as specified by ISO 10140-1 standard for glass panels. The contribution of the internal losses can be isolated by applying this procedure to suspended beams. The radiation losses, as well as the sound radiation efficiency, can be calculated according to Leppington's classic theory [10] on the basis of the apparent bending stiffness.

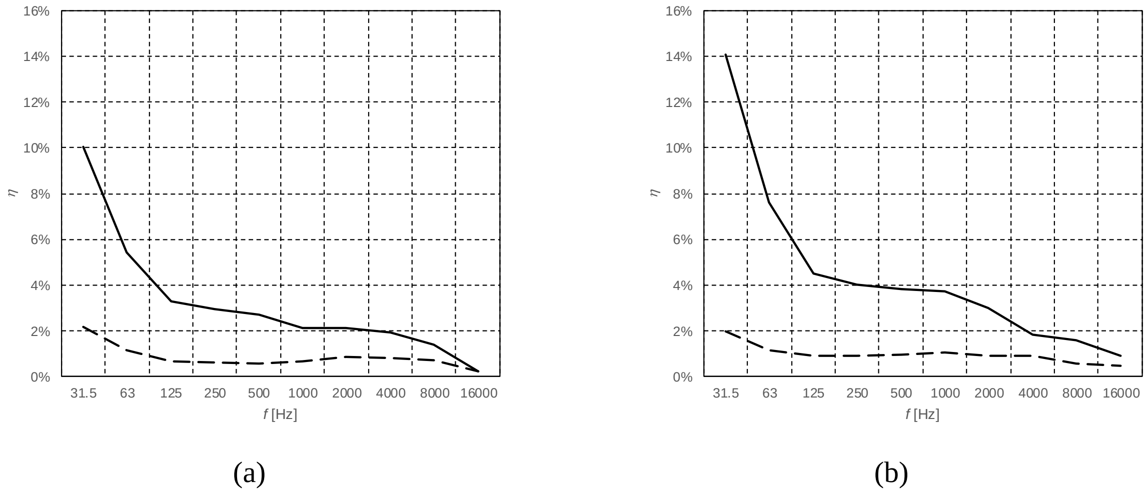
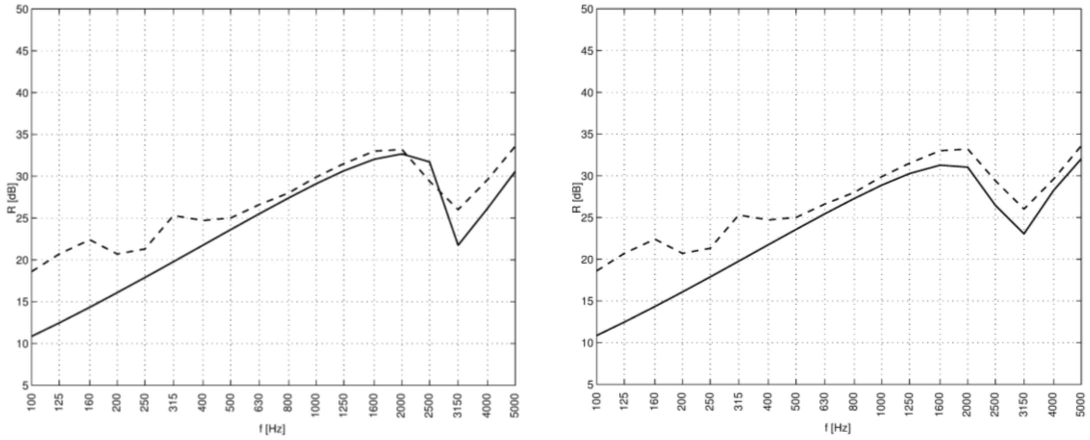


Figure 4: Losses for plasterboard (a) and gypsum fibreboard (b). Dashed line: internal losses; solid line: internal losses + losses due to adjoining structures.

3. Results

3.1 Plasterboard

Figure 5 shows the comparison between measured and predicted sound reduction index, the latter being obtained with the two methods described in Sections 2.1.1 and 2.1.2.



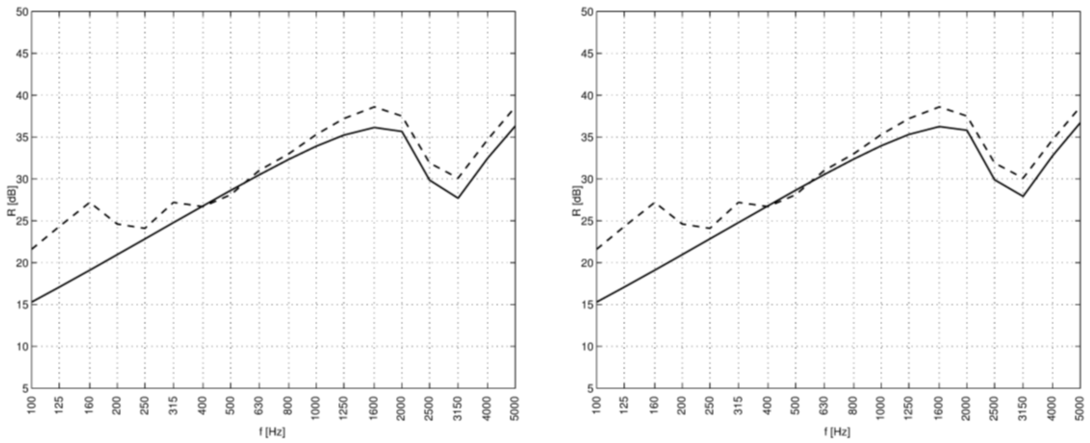
(a) (b)

Figure 5: Comparison between measured (dashed line) and predicted (solid line) *R* for plasterboard. Predictions based on natural frequencies measured on a beam (a) and mobility measurements on a plate (b).

It can be observed that:

- Predicted sound reduction index values considerably differ from sound transmission room measurements in low-frequency range. This is mainly due to the so called "baffle effect", which is particularly evident since the tested panel is far smaller than the dividing surface between the two chambers.
- In the coincidence region the predictions look more accurate, even if the critical frequency is slightly underestimated by the natural frequency method.
- Above the coincidence region, the mobility method seems to provide better estimation.

3.2 Fibre-reinforced board



(a) (b)

Figure 6: Comparison between measured (dashed line) and predicted (solid line) *R* for fibre-reinforced board. Predictions based on natural frequencies measured on a beam (a) and mobility measurements on a plate (b).

Figure 6 shows the comparison between measured and predicted sound reduction index, the latter being obtained with the two methods described in Sections 2.1.1 and 2.1.2.

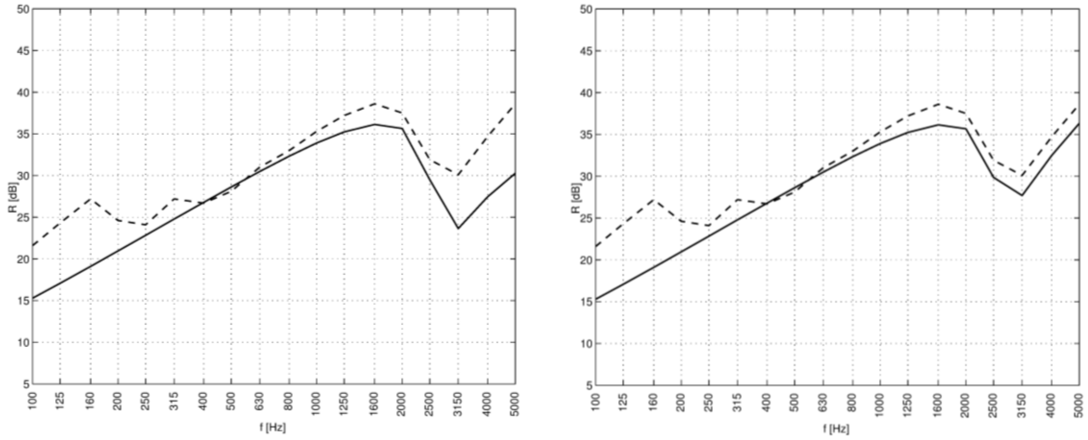
It can be observed that:

- Natural frequency and point mobility methods provide very similar results.
- As for plasterboard, predicted sound reduction index values considerably differ from sound transmission room measurements in low-frequency range due to baffle effect.
- In the mid-high frequency range, the difference between measured and predicted curves is around 2 dB.

3.3 Discussion

The predicted sound reduction index curves shown in Figs. 5 and 6 have been obtained with limiting angle of incidence of 83°, which is consistent with the empirical values known to provide good agreement between measured and calculated values [11].

As pointed out in [12], the lack of an accurate evaluation of the losses leads to the underestimation of the sound reduction index around and above the coincidence region. For instance, if the solid-line curve in Fig. 6(a) had been obtained without considering η_{int} and η_{adj}, the comparison between experimental and predicted curves would have looked like Fig. 7(a).



(a) (b)

Figure 7: Gypsum fibreboard – Comparison between predicted (solid line) and measured (dashed line) *R*, without considering internal and adjoining-structure losses (a) and including them in the calculation (b).

4. Conclusions

The aim of the work is to evaluate the applicability to homogeneous panels of two diagnostic procedures designed for the determination of the dynamic and acoustic characteristics of composite structures. In the present paper, the sound reduction indices of two type of materials, obtained from natural frequency measurements on a beam, and point mobility measurements on a panel, have been compared to sound transmission room results.

Both models produce fair agreement in the medium and high frequency range, provided that the losses are determined in an accurate way using the reverberation time technique. On the other hand, in the low frequency range, predictions considerably differ from experimental results due to the small size of the panels tested in sound transmission room, whereas both the investigated models are for infinite plates. It is worth noting that the main application of plasterboard and gypsum fibreboard is in building walls and ceilings, whose size would limit the baffle effect to very low frequencies. However, if the sound reduction index of small panels is to be modelled, corrections to account for this phenomenon should be applied.

The determination of natural frequencies on a beam cut from the material confirms its potential with a relatively simple procedure and robust results. The point-mobility method requires experienced measurements and more fine tuning in the post-processing stage. In particular, results can be improved by enhancing the quality of the experimental data and their elaboration in the low frequency range, where the modal density is poor.

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